Calibration update

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University of Sheffield

DUNE UK Project Meeting, July 4th 2023

Introduction

The Sheffield group is currently involved in a number of calibration tasks,

- **Neutral pion** studies for electromagnetic shower calibration [Praveen Kumar]
  - DUNE FD, cosmics
- **Stopping muon** calibration [Praveen Kumar]
  - DUNE FD, cosmics
- **Absolute energy scale** calibration [Rhiannon Jones]
  - DUNE FD, cosmics
  - ProtoDUNE SP (HD pending), beam & cosmics
- Collaborative efforts across DUNE working groups and consortia [Calibration WG]

I will run through a *brief* summary of each.

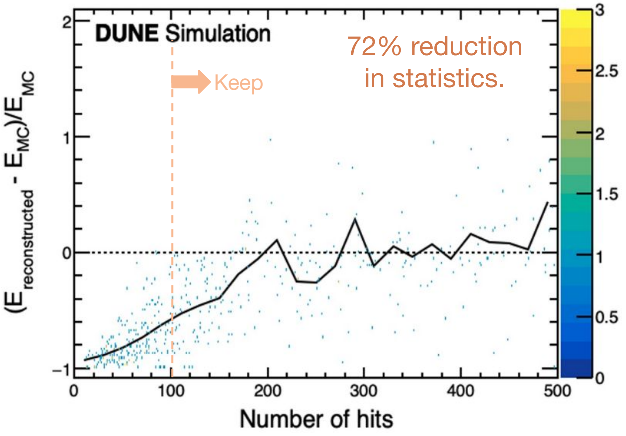
Neutral pions

DUNE collaboration meeting, May 2023

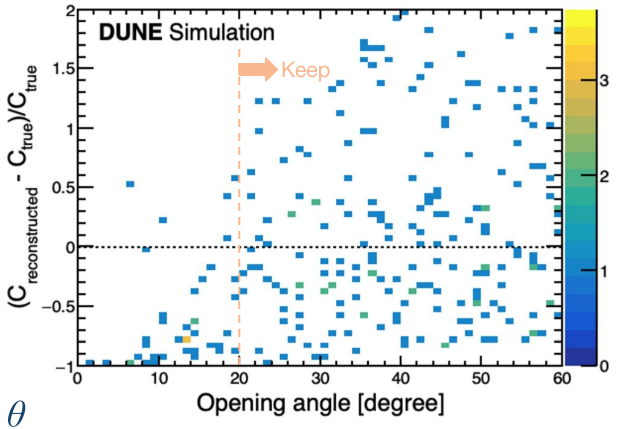
Praveen Kumar

Overview of the study

- Studied cosmic muon-induced neutral pions in the HD DUNE FD module
  - Assessed reconstruction capabilities between the neutrino-oriented Pandora reconstruction chain and the cosmic-oriented reconstruction chain
  - He found that the neutrino-oriented reconstruction fared better than the track-oriented cosmic chain
- Sample contents and selection
  - ~1.5 million simulated cosmic muons (104 days)
  - Events with at least one $\pi^0 \rightarrow 2\gamma$ (truth level)
  - Highest energy pair of showers taken in events with ≥ 2 reconstructed showers
  - Must be >100 hits in a shower
  - Opening angle between showers must be >20°



8% reduction in statistics.
Cut reduces bias but cannot improve invariant mass resolution.



$$C = 1 - \cos\theta$$

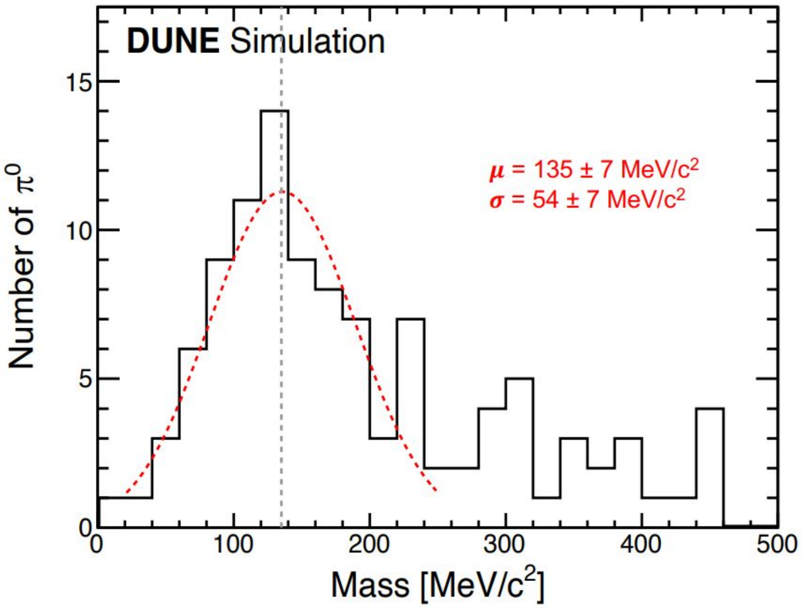
Neutral pions

Results

- Following the selection there are 156 π^0s
  - Corresponds to ~1.5/day
- The π^0 invariant mass, W, is calculated,

$$W = \sqrt{2E_1 E_2 (1 - \cos\theta)}$$

- Extract W = 135 ± 54 MeV/c^2
- There is no bias on this measurement, however the statistics are low and the resolution is poor
- Truth-level quantities are still being used, will be interesting to assess the fully-reconstructed case



Stopping muons

Praveen Kumar

DUNE

Overview of the study

- Replicate ProtoDUNE and MicroBooNE recombination (Modified Box model) calibration method using stopping muons in the HD DUNE FD module
  - Challenge: **very** few stopping muons ~80/day
    - Statistics mean we cannot construct (good) charge deposition maps for dQ/dx calibration
  - Skip straight to dE/dx, extract C_{Cal}

$$\left(\frac{dE}{dx}\right)_{\text{Cal}} = \frac{\exp\left(\frac{dQ/dx}{\boxed{C_{\text{Cal}}}} \cdot \frac{\beta W_{\text{ion}}}{\rho\epsilon}\right) - \alpha}{\beta/\rho\epsilon}$$

dQ/dx	=	Charge depositions [ADC/cm]
C_{Cal}	=	Calibration constant [ADC/e$^-$]
$C_{Cal,\,nom}$	=	5 x 10^{-3} [ADC/e$^-$]
W_{ion}	=	23.6 x10^{-6} [MeV/electron]
ε	=	0.5 [kV/cm] (electric field strength)
ρ	=	1.38 [g/cm^3] at 124.106 kPa
β	=	0.212 [(kV/cm)(g/cm^3)/MeV]
α	=	0.93

2020 JINST 15 P12004
2013 JINST 8 P08005

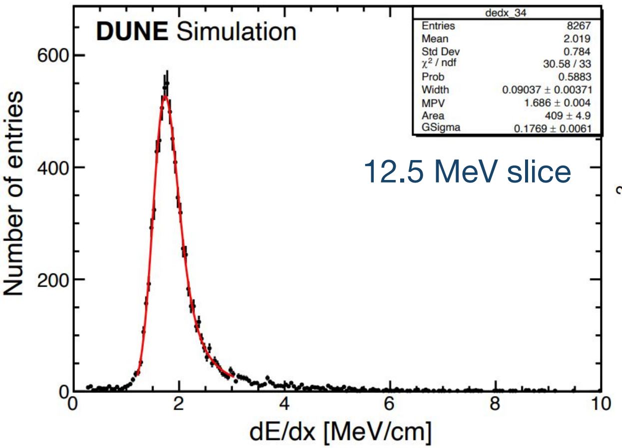
Stopping muons

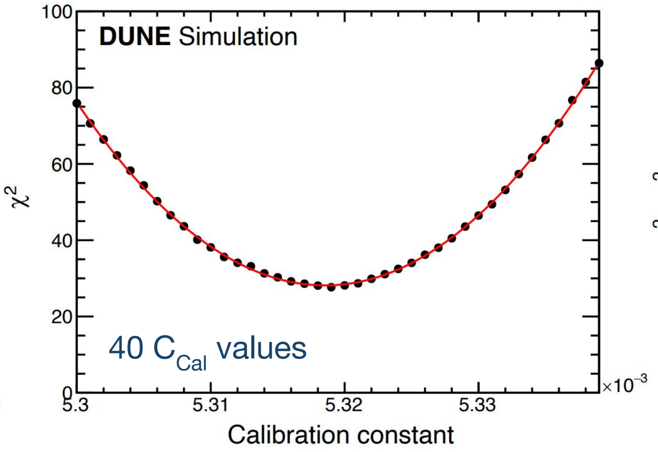
C_{Cal} extraction

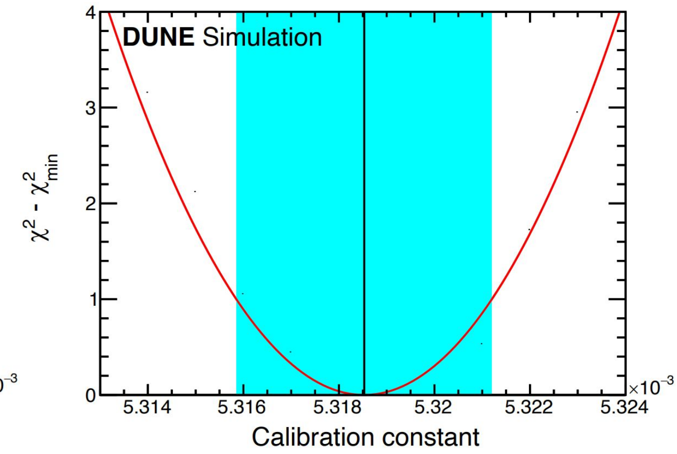
Inject a range of C_{Cal} values & extract dE/dx vs residual range (RR) [/KE]. Slice in the MIP region (KE 250-450 MeV)

Extract dE/dx_{MPV} per slice and calculate χ^2 across the MIP region for each C_{Cal} dE/dx vs RR [/KE] distribution.

$C_{Cal} = (5.319 \pm 0.003) \times 10^{-3}$ [ADC/e^-]



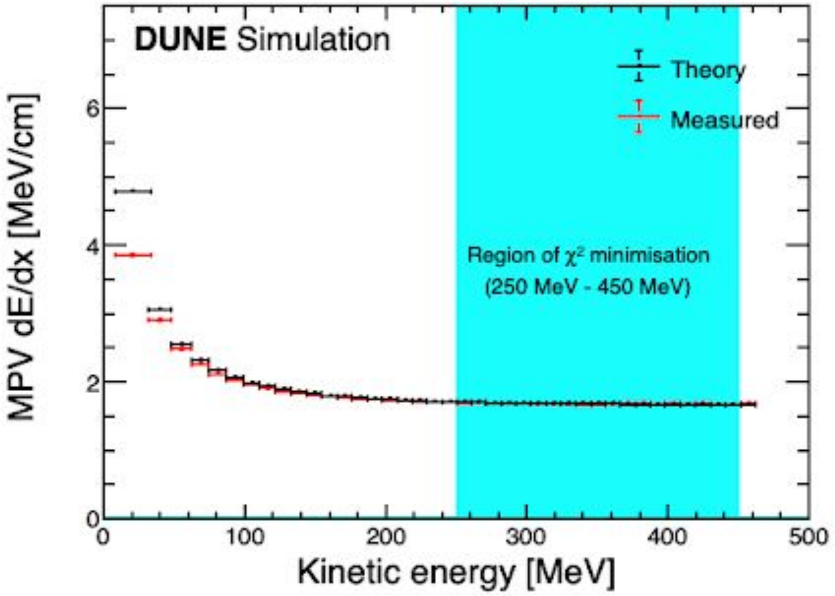


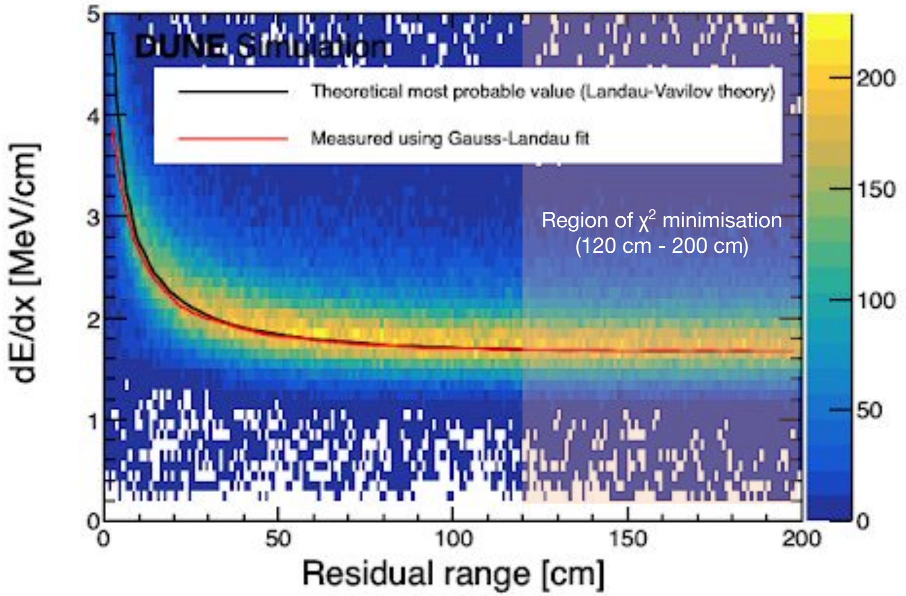


$$\chi^2 = \sum \left(\frac{(dE/dx_{MPV,Predicted} - dE/dx_{MPV,Measured})^2}{\sigma^2} \right)$$

Stopping muons

Results





A good fit in the MIP region, need to tune other parameters to improve lower KE/RR region.

Absolute energy scale

Absolute energy scale at the DUNE HD FD

- Initially looked at through-going cosmic-ray muons at the DUNE FD
- The calibration procedure looked a little something like this

Select **reconstructed** muons with the following criteria:

- **PFPrimary** - to maximise primary purity
- $\mathbf{L_{Reco} > 2\ m}$ - to maximise muon purity
- $\mathbf{N_{\delta}/L_{Reco} > 17\times10^{-3}\ cm^{-1}}$ - to minimise energy-dependence

Absolute energy scale

DUNE collaboration meeting, May 2023

Rhiannon Jones

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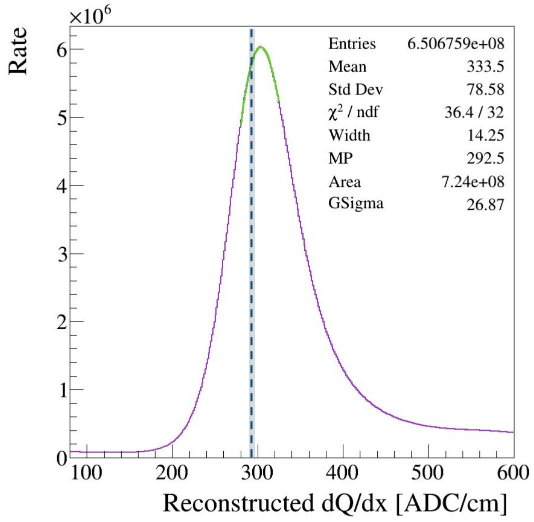


MP error is:

$$\sigma_{MP} = \sqrt{\sigma^2_{\mathrm{MP,fit}} + \sigma^2_{E_{dep}} + \sigma^2_{\tau} + \sigma^2_{N}}$$

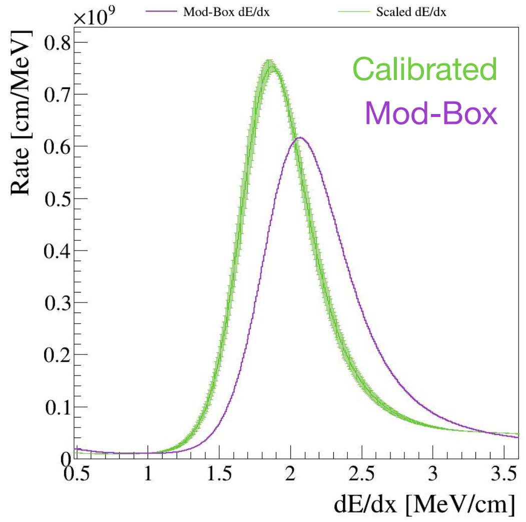
$\sigma^2_{\mathrm{MP,fit}}$: From the fit; $\sigma^2_{E_{dep}}$: Energy-dependence; σ^2_{τ}: Lifetime; σ^2_{N}: Stats

Scale factor: **S = dE/dx$_{L\text{-}V}$ / dQ/dx$_{MP}$**

S = (6.16 ± 0.08) x10^{-3} [MeV/ADC] (stat+syst, 1.23%)

dE/dx$_{L\text{-}V}$ = 1.804 MeV/cm (μ: 292 GeV @ 5.3 mm pitch)

https://lar.bnl.gov/properties/



Absolute energy scale in ProtoDUNE SP

I have been looking at applying the DUNE FD calibration procedure on ProtoDUNE muons.

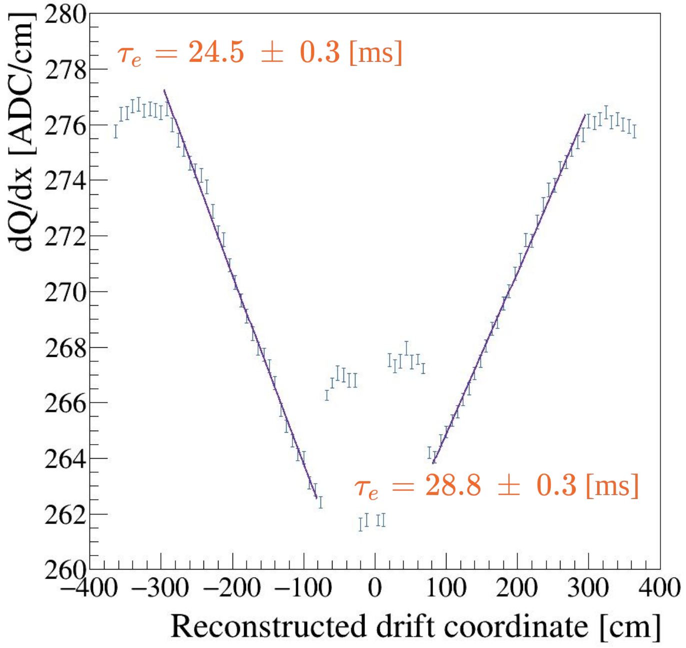
- 1 GeV ProtoDUNE-SP beam particles ~30k muons
  - Large fraction of these muons come from the halo, skewing the average energy up to **~9 GeV**
- 7 GeV ProtoDUNE-SP beam particles ~100k muons
  - Halo contributions skew the average energy to **~6 GeV**
- Cosmics ~8M muons

So far it's all MC only, but the wheels are in motion to apply this effort to PD-SP data.

Absolute energy scale

Absolute energy scale in ProtoDUNE SP

- Implemented **Viktor's** DUNE FD electron lifetime calculation using the ProtoDUNE **cosmics**
  - Used to correct the dQ/dx using the FD approach
  - Not the same as the ProtoDUNE extraction
- The energy scale is then calculated from reconstructed charge depositions in the 1 & 7 GeV (halo-dominated) beam samples
- Currently, only a single systematic is considered to account for the energy dependence of dQ/dx
- *The impact of space charge is currently being investigated - no correction implemented currently*



Cosmic muons

Absolute energy scale

Rhiannon Jones

Absolute energy scale in ProtoDUNE SP

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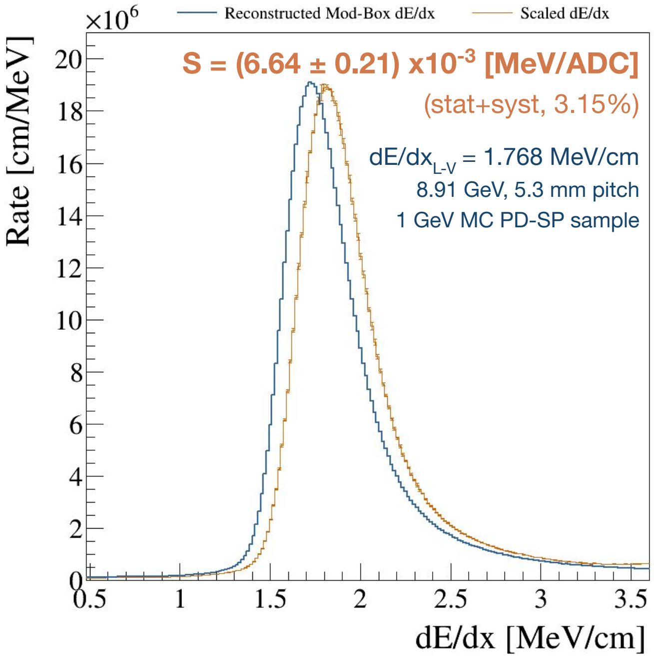
$S = dE/dx_{L\text{-}V} / dQ/dx_{MP}$



8.91 GeV beam muons

Absolute energy scale

Absolute energy scale in ProtoDUNE SP

$S = dE/dx_{L\text{-}V} / dQ/dx_{MP}$

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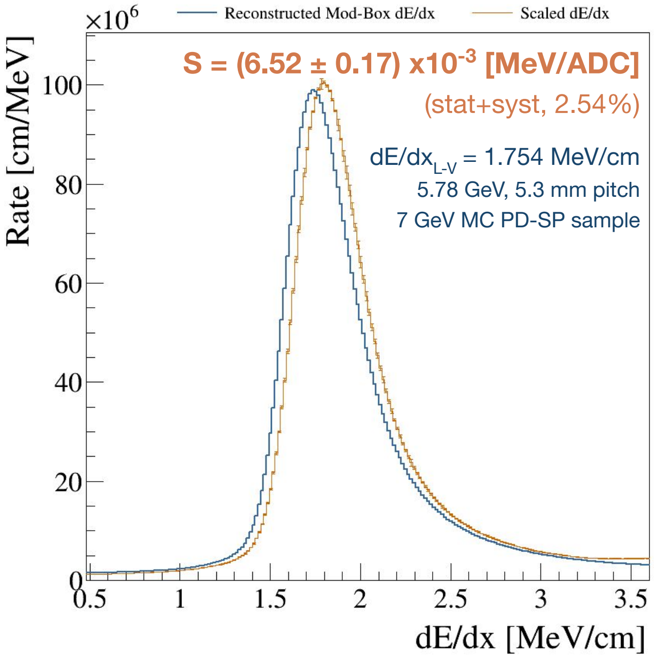


5.78 GeV beam muons

Calibration working group

Current areas of focus

- Cosmic rays & muons for
  - Electron lifetime (HD & VD)
  - Energy scale (HD, VD & PD)
  - Stopping muons/particles (HD, VD & PD)
  - π^0 and EM shower calibrations (HD & VD)
- Neutron calibration
  - ARTIE-II
  - Low-energy ML classification, BLIPS
- Vertical drift calibration
  - Electron lifetime
  - Absolute energy scale
- Collaboration with CALCI

Plans

- *Very* preliminary: working on a plan for a few publications, possibilities include,
  - Cosmic-ray muon DUNE FD calibration and/or
  - Calibration scope for DUNE FD phase I
- Continue checking in with CALCI & ProtoDUNE DRA
- Extend liaisons to other working groups
  - VD
  - ND
  - TPC electronics
  - Physics analysis groups
  - …

Direct effort by Sheffield/UK

Thank you!

Neutral pions

Praveen Kumar

Summary and next steps

Summary,

- Neutral pions from cosmic-ray muons are difficult to use for EM shower calibration
- Laid out a procedure for understanding the status of the shower reconstruction
- This can now be built upon as we aim to improve our electromagnetic shower reconstruction capabilities

Next steps for this work include,

- Construct a fully-reconstructed selection of the neutral pions
- Defining a targeted reconstruction chain for the environment we are dealing with
  - Muon-induced neutral pions, no neutrino vertex, possibility of high multiplicities of electromagnetic showers

Stopping muons

DUNE collaboration meeting, May 2023

Praveen Kumar

DUNE

Summary and next steps

Summary,

- Good progress but there are limitations
  - Other parameters in the Modified Box recombination model need to be known
  - Low statistics - not much we can do!

Modified Box model

$$\left(\frac{dE}{dx}\right)_{\text{Cal}} = \frac{\exp\left(\frac{dQ/dx}{C_{\text{Cal}}} \cdot \frac{\beta W_{\text{ion}}}{\rho\epsilon}\right) - \alpha}{\beta / \rho\epsilon}$$

Next steps for this work include,

- Apply the calibration to charged pions to see whether it can reproduce their dE/dx dependence on the range and energy of a pion.
- Try a method that can remove the dependence on α & β

Absolute energy scale

Next steps

- Run the method on ProtoDUNE data
  - After some final analysis tweaks (inc. SCE correction)
- Validate this absolute energy scale method using the standard stopping muon calibration procedure applied to
  - A-C-crossing muons in ProtoDUNE
  - FD muons (extending Praveen’s work)
  - How well does Mod-Box calibration match absolute calibration?
- Turn attention to other particle types
  - Look at existing measurements
  - What can we do with external data?

1 GeV beam muons, ProtoDUNE-SP, truth

Statistic	Rate / 291.8 Days	% Long TPC μ
Events	82,330	-
TPC μ	32,489	133.11 %
Primary TPC μ	32,476	133.05 %
Long TPC μ	24,408	100 %
Crosses top or bottom	3380	13.848 %
Crosses top and bottom	0	0 %
Crosses front or back	23,946	98.107 %
Crosses front and back	12,097	49.562 %
Crosses 1 APA or CPA	1514	6.2029 %
Crosses $\geq$ 2 APA or CPA	0	0 %
Stopping	8496	34.808 %
Exiting	15,912	65.192 %

7 GeV beam muons, ProtoDUNE-SP, truth

Statistic	Rate / 223.1 Days	% Long TPC μ
Events	62,980	-
TPC μ	106,078	131.92 %
Primary TPC μ	105,925	131.73 %
Long TPC μ	80,408	100 %
Crosses top or bottom	1116	1.3879 %
Crosses top and bottom	0	0 %
Crosses front or back	71,797	89.291 %
Crosses front and back	40,004	49.751 %
Crosses 1 APA or CPA	10,937	13.602 %
Crosses $\geq$ 2 APA or CPA	0	0 %
Stopping	18,516	23.028 %
Exiting	61,892	76.972 %

Cosmics, ProtoDUNE-SP, truth

Statistic	Rate / 291.8 Days	% Long TPC μ
Events	82,330	-
TPC μ	7,709,038	100 %
Primary TPC μ	7,709,038	100 %
Long TPC μ	7,708,782	100 %
Crosses top or bottom	6,340,934	82.256 %
Crosses top and bottom	1,070,659	13.889 %
Crosses front or back	3,151,080	40.876 %
Crosses front and back	74,610	0.96786 %
Crosses 1 APA or CPA	3,493,602	45.32 %
Crosses $\geq$ 2 APA or CPA	403,034	5.2282 %
Stopping	1,840,093	23.87 %
Exiting	5,868,689	76.13 %

1 GeV beam muons, ProtoDUNE-SP, reco

Statistic	Rate / 291.8 Days	% $\mu > 3$ m
Events	82,330	-
Tracks	331,504	2559.5 %
Muons	55,535	428.78 %
$\mu > 3$ m	12,952	100 %
Crosses top or bottom	1063	8.2072 %
Crosses top and bottom	52	0.40148 %
Crosses front or back	12,528	96.726 %
Crosses front and back	7449	57.512 %
Crosses 1 APA or CPA	1162	8.9716 %
Crosses $\geq$ 2 APA or CPA	0	0 %
Stopping	4030	31.115 %
Exiting	8620	66.553 %

7 GeV beam muons, ProtoDUNE-SP, reco

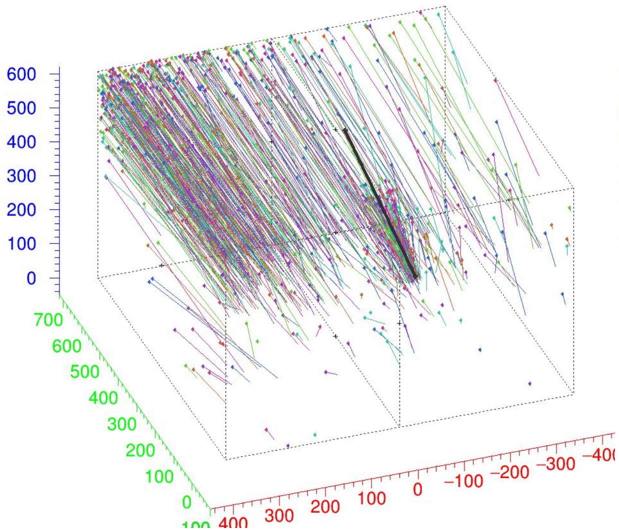
Statistic	Rate / 223.1 Days	% $\mu > 3$ m
Events	62,980	-
Tracks	4,226,034	7826.9 %
Muons	236,766	438.5 %
$\mu > 3$ m	53,994	100 %
Crosses top or bottom	6024	11.157 %
Crosses top and bottom	261	0.48339 %
Crosses front or back	48,695	90.186 %
Crosses front and back	31,212	57.806 %
Crosses 1 APA or CPA	12,633	23.397 %
Crosses ≥ 2 APA or CPA	22	0.040745 %
Stopping	10,522	19.487 %
Exiting	38,773	71.81 %

Cosmics, ProtoDUNE-SP, reco

Statistic	Rate / 35.43 Days	% $\mu > 3$ m
Events	10,000	-
Tracks	1,264,192	437.29 %
Muons	1,008,211	348.75 %
$\mu > 3$ m	289,095	100 %
Crosses top or bottom	240,240	83.101 %
Crosses top and bottom	80,469	27.835 %
Crosses front or back	103,513	35.806 %
Crosses front and back	5234	1.8105 %
Crosses 1 APA or CPA	132,024	45.668 %
Crosses ≥ 2 APA or CPA	22,522	7.7905 %
Stopping	55,063	19.047 %
Exiting	217,778	75.331 %

ProtoDUNE samples: Visualising the true muons

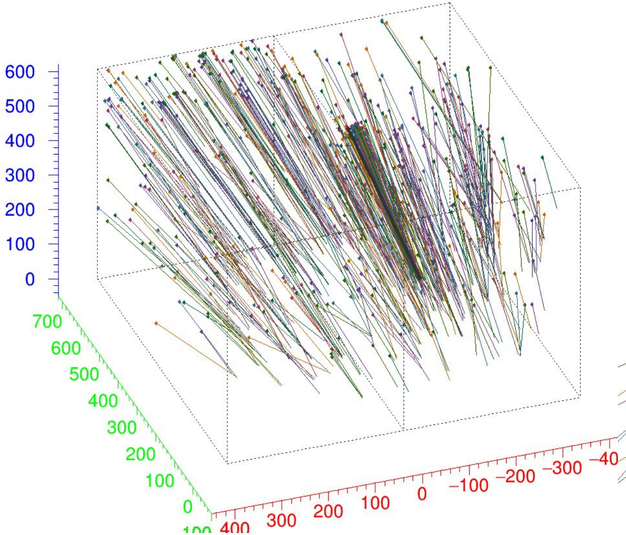
1 GeV beam muons



65% exiting

Lower energy → higher halo activity.

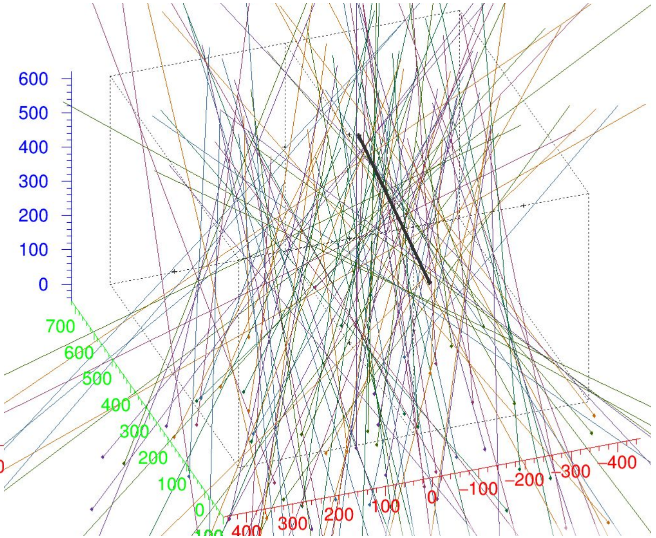
7 GeV beam muons



77% exiting

Higher energy → higher beam plug activity.

Cosmics

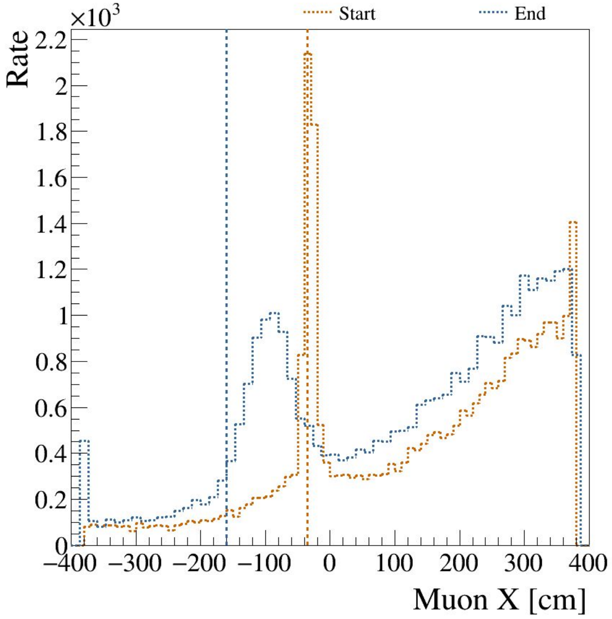


76% exiting

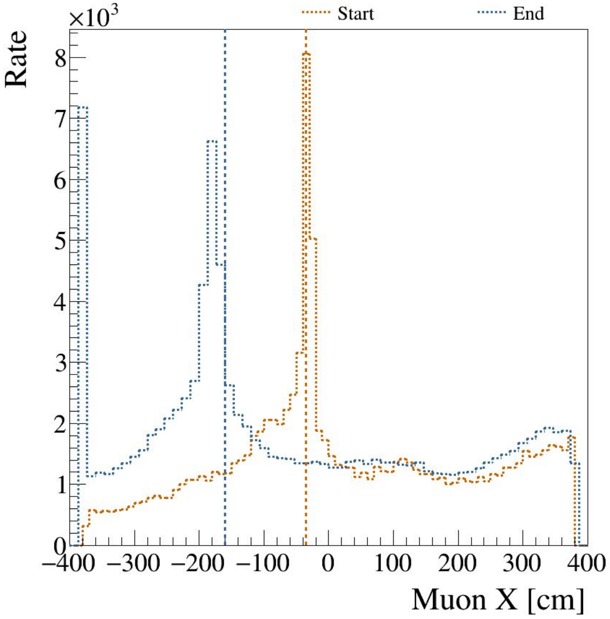
Surface-level cosmics, pretty sporadic.

ProtoDUNE samples: True start x position

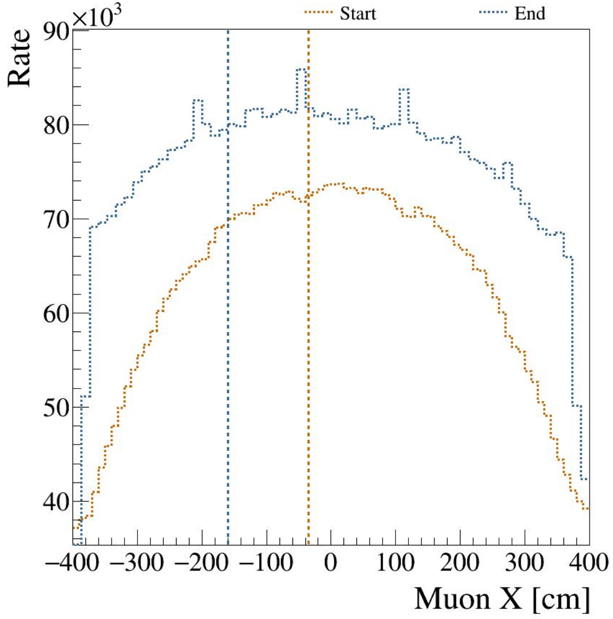
1 GeV beam muons



7 GeV beam muons

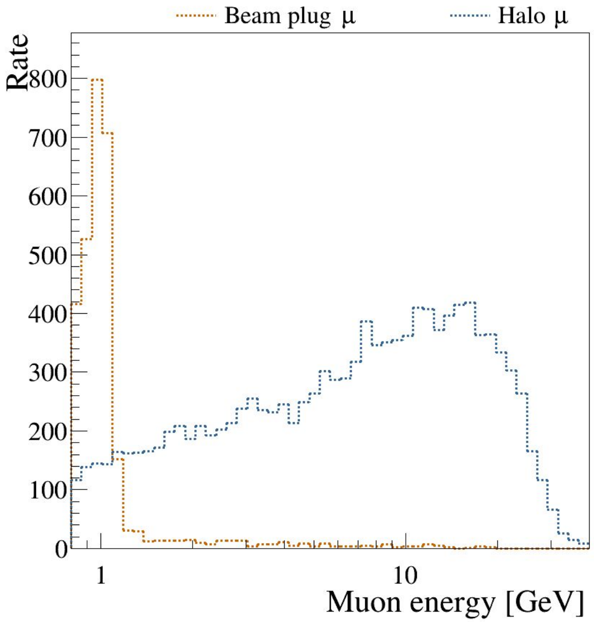


Cosmics

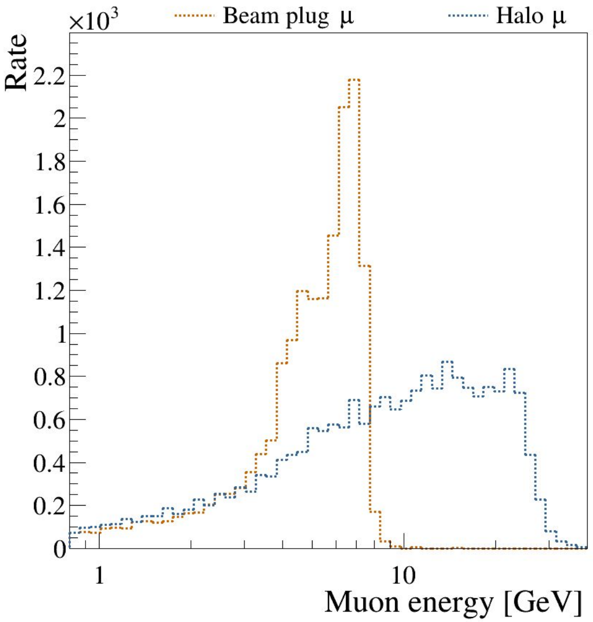


ProtoDUNE samples: True muon energies

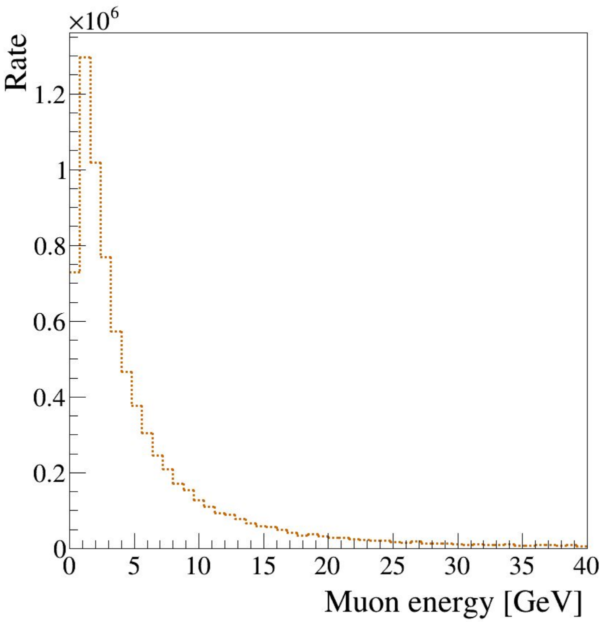
1 GeV beam muons



7 GeV beam muons

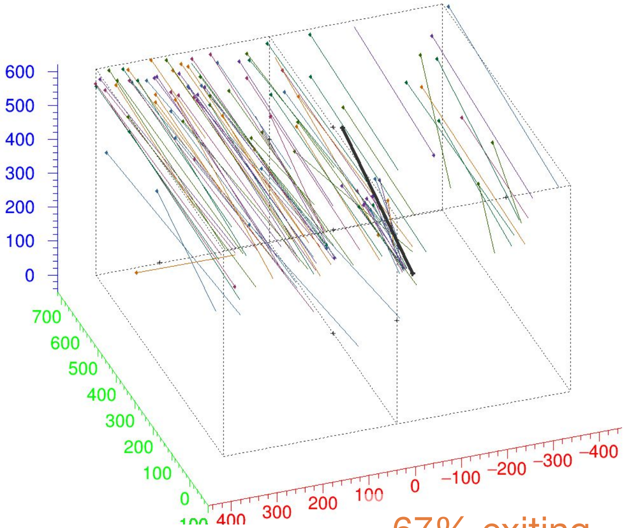


Cosmics



Reconstructed muons (fewer shown than in truth)

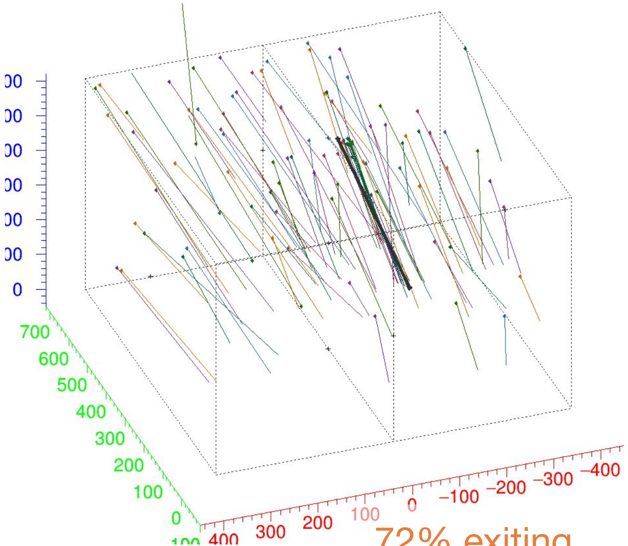
1 GeV beam muons



67% exiting

Lower energy → higher halo activity.

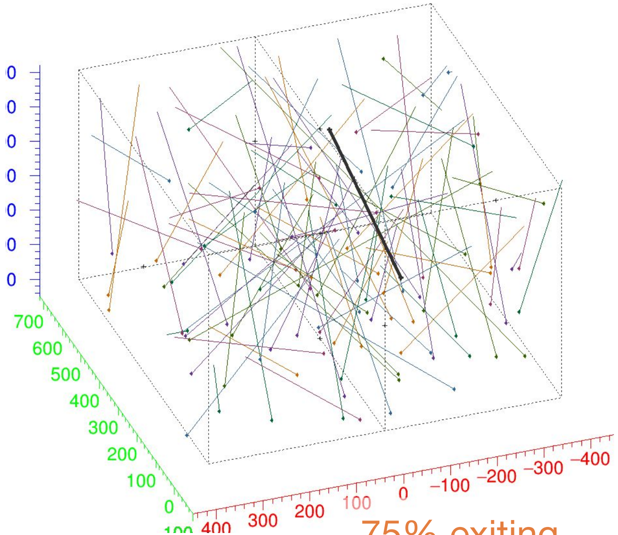
7 GeV beam muons



72% exiting

Higher energy → higher beam plug activity.

Cosmics

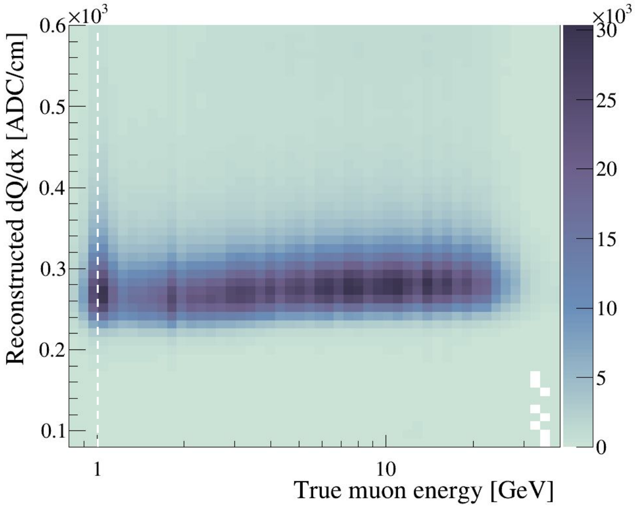


75% exiting

Surface-level cosmics, pretty sporadic.

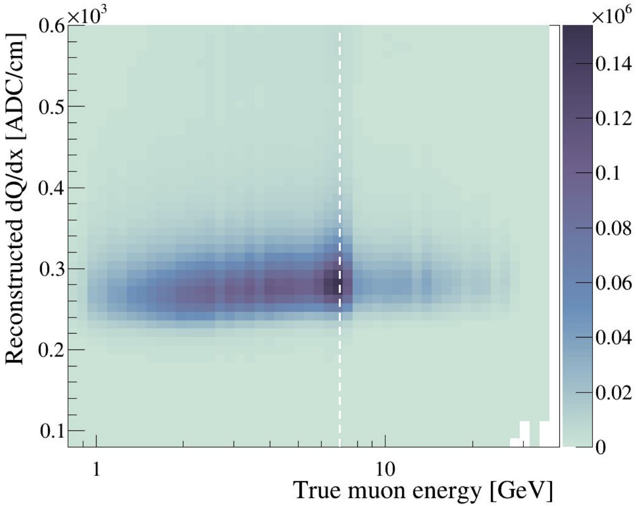
Reconstructed muons: τ_e-corrected dQ/dx

1 GeV beam muons



Clear peak at 1 GeV and large statistical and energy contributions from the halo.

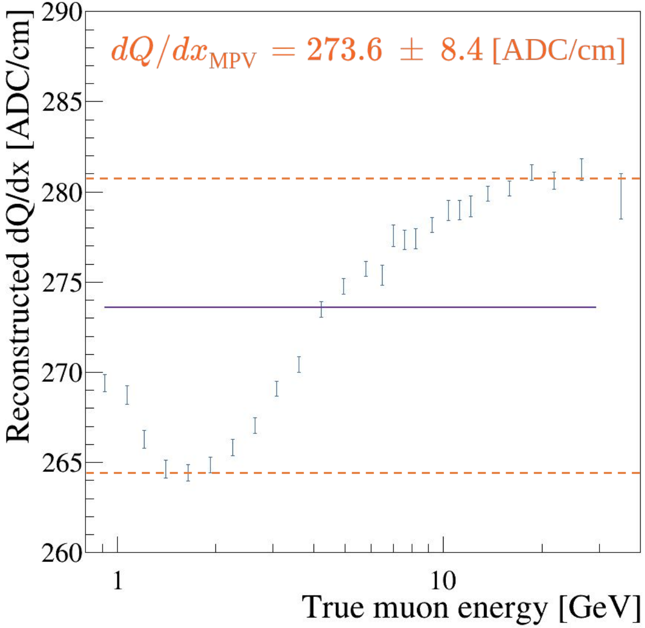
7 GeV beam muons



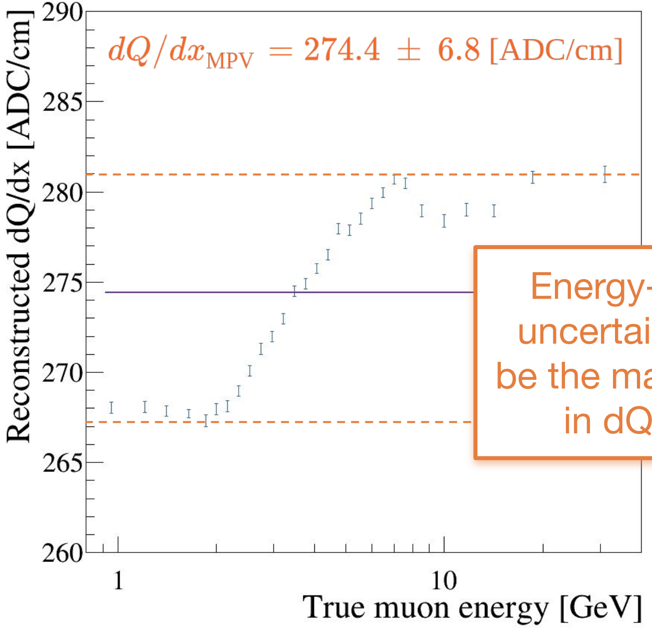
Clear peak at 7 GeV, lower-energy tail and lower statistical contributions from the halo.

Reconstructed muons: MP dQ/dx extraction

1 GeV beam muons

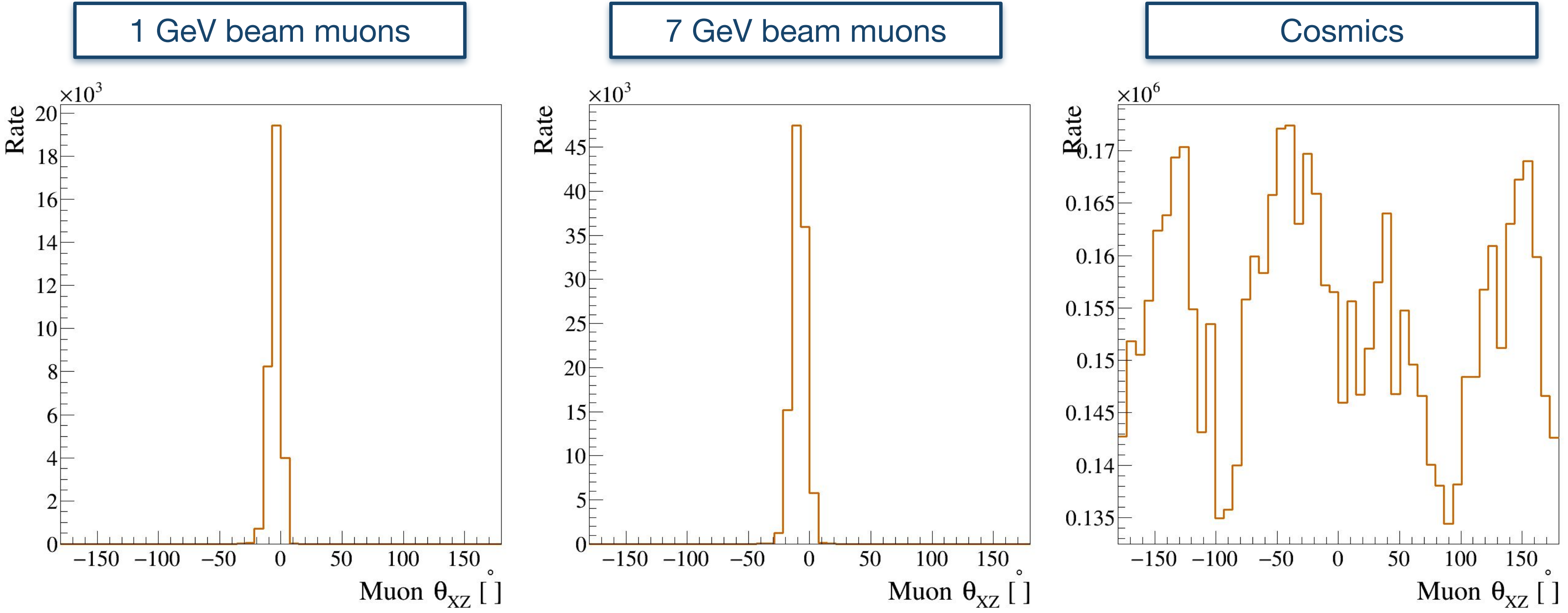


7 GeV beam muons



Energy-dependence uncertainty defined to be the maximal variation in dQ/dx values.

ProtoDUNE samples: True θ_{XZ}

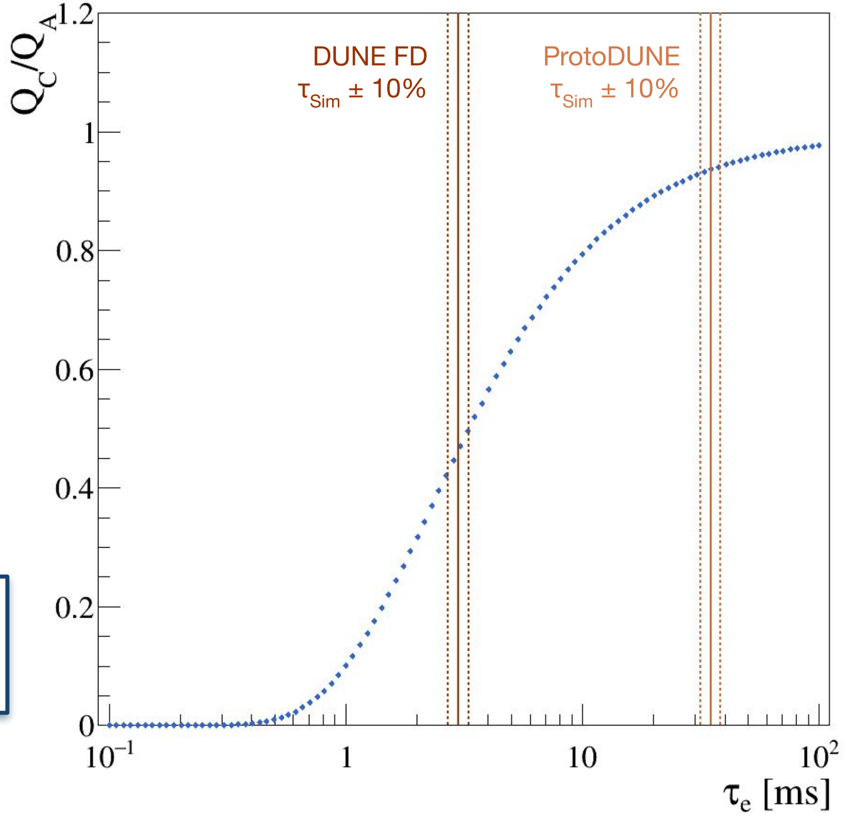


ProtoDUNE lifetime calculation

$$\frac{Q_c}{Q_a} = \exp\left(\frac{-t_{fulldrift}}{\tau}\right)$$

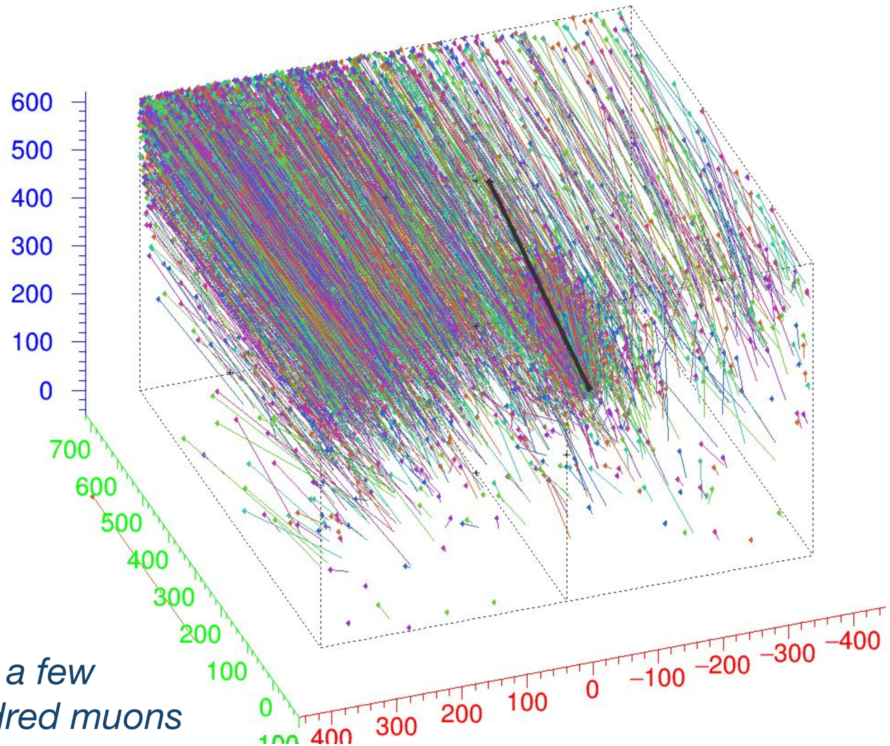
2020 JINST 15 P12004

- The values of τ_e presented on the previous slide vary substantially from the simulated value for many reasons & I don't want to reinvent the wheel
  - I will look into doing this properly before looking at data
- Whilst setting up the energy scale calibration tools to work at ProtoDUNE I will likely correct for the simulated lifetime to begin with
- I have instead evaluated the likely impact of a variation in the lifetime on the charge depositions at ProtoDUNE compared with the Far Detector (RHS)

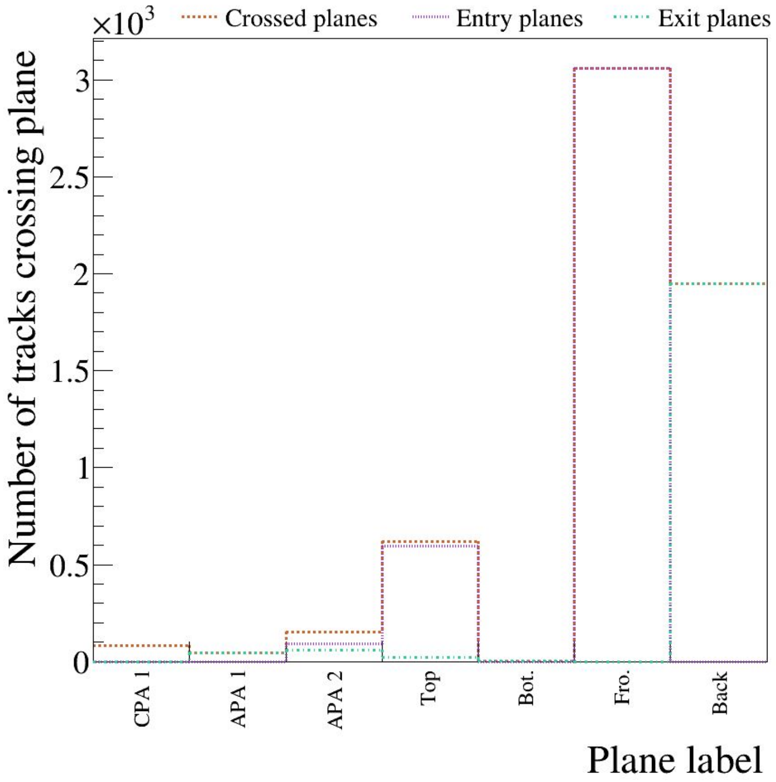


A 10% variation in τ_e corresponds to a variation in Q_a/Q_c of:
15.4% at the FD 1.3% at ProtoDUNE

Looking at the muons



Only a few hundred muons



Location of the beam plug

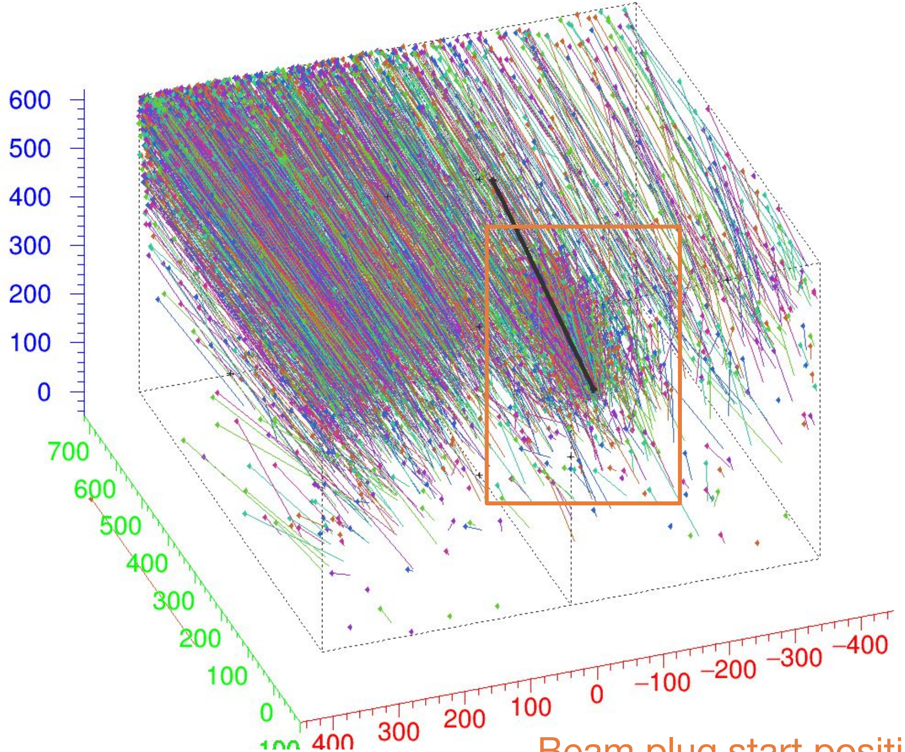
The black line shows the location of the beam plug on the front face of the detector, and is projected along its direction onto the back face of the detector.

The activity surrounding this path is clear in the high-intensity plot on the RHS.

The angle of the beam is:

"It points down 11° from the horizontal, and towards the APA on the negative x side, 10° to the right of the z direction."

From the First Results paper.

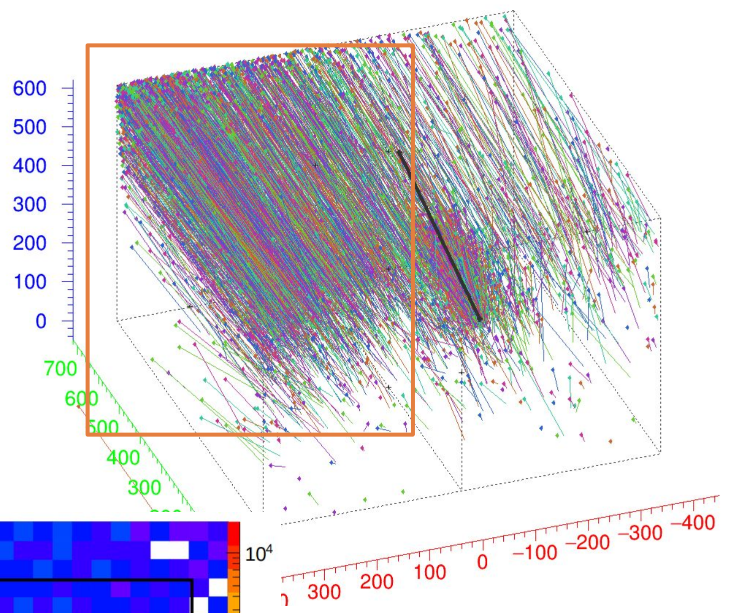


Beam plug start position:

(-34.52, 431.90, 0.00) cm

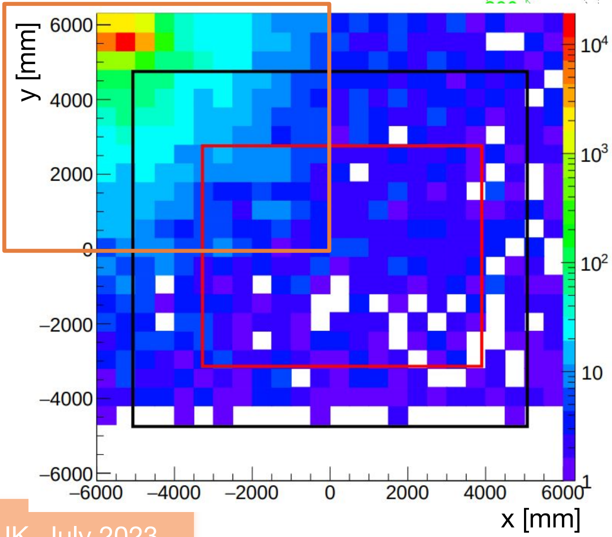
Taken from the ProtoDUNE gdml files

Location of the beam plug



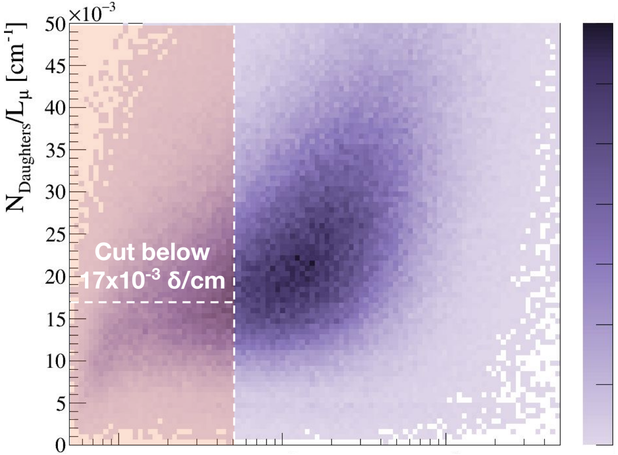
There is also a known ‘muon halo’ which originates from the decay of charged pions as they travel along the beamline, resulting in muons entering the TPC *“slightly upward and sidewards of the H4 beamline”.* ProtoDUNE TDR.

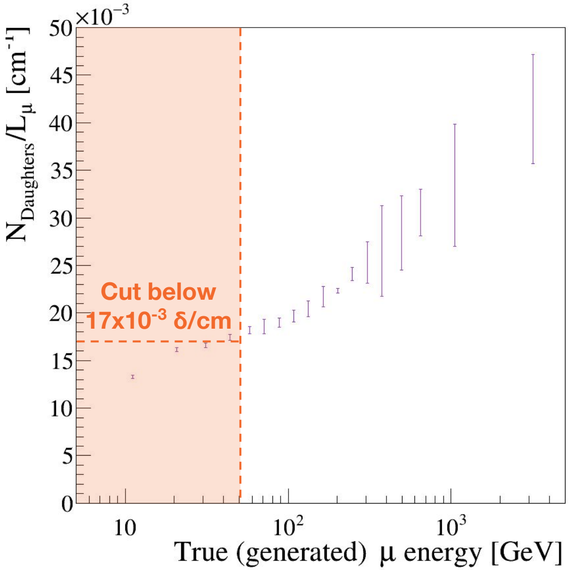
According to the TDR this should be in the negative x-direction, however I’m not **yet** confident in the consistency of the direction definitions and looking at the TDR’s expected behaviour of this halo I’m reasonably convinced that this is what we’re seeing.



Sample tuning

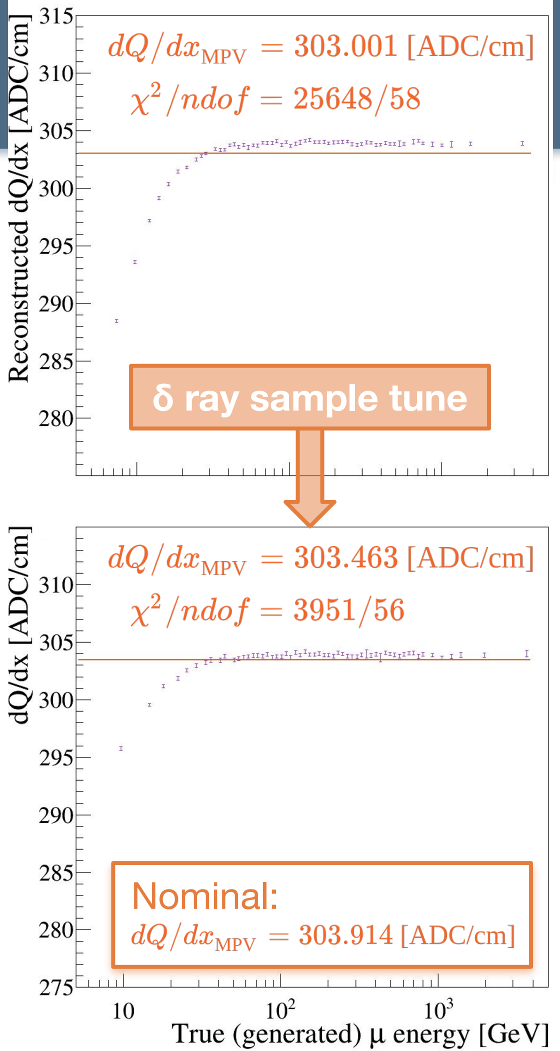
- Use the rate of δ-ray activity surrounding the CR muons to characterise the energy dependence of the charge depositions
- Cut muons with fewer than 17×10^{-3} δ/cm from the sample to mitigate some of the energy dependence below 50 GeV
  - This corresponds to a ~9% reduction in the statistics





Sample tuning

- Use the rate of δ-ray activity surrounding the CR muons to characterise the energy dependence of the charge depositions
- Cut muons with fewer than 17×10^{-3} δ/cm from the sample to mitigate some of the energy dependence below 50 GeV
  - This corresponds to a ~9% reduction in the sample statistics
- Recalculate the best-fit value of dQ/dx after cutting the sample to quantify the reduced energy dependence
- Define a systematic parameter which quantifies the effect and apply the residual variation as an uncertainty on the energy scale measurement



Reconstructed dE/dx

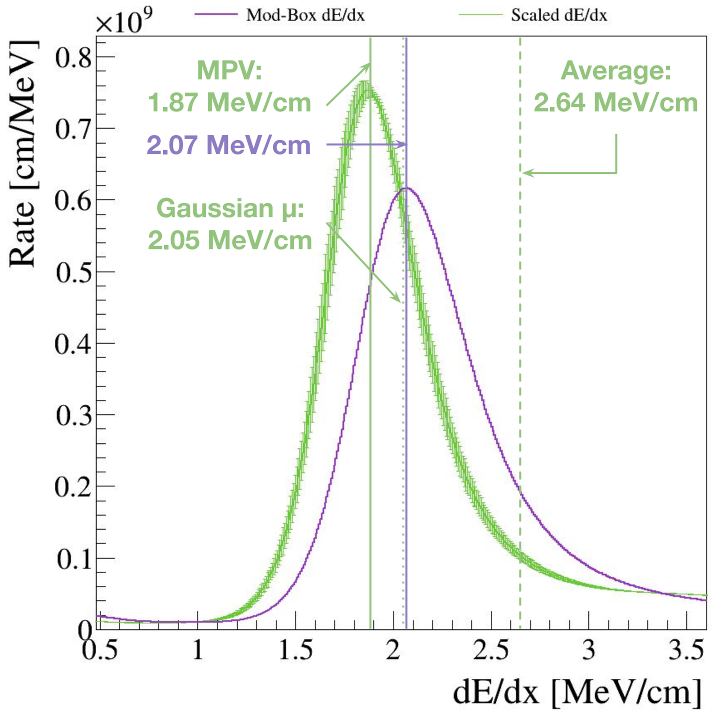
This absolute energy-scale calculation on 'data' can be extremely simple, owing to the lack of energy reconstruction:

Fit a Landau x Gaussian to dQ/dx in 1D and scale to the L-V dE/dx for the average energy and thickness.

The uncertainties were applied by throwing 2000 toys within the 1σ scale-factor uncertainty and extracting the 1σ dE/dx uncertainty from that.

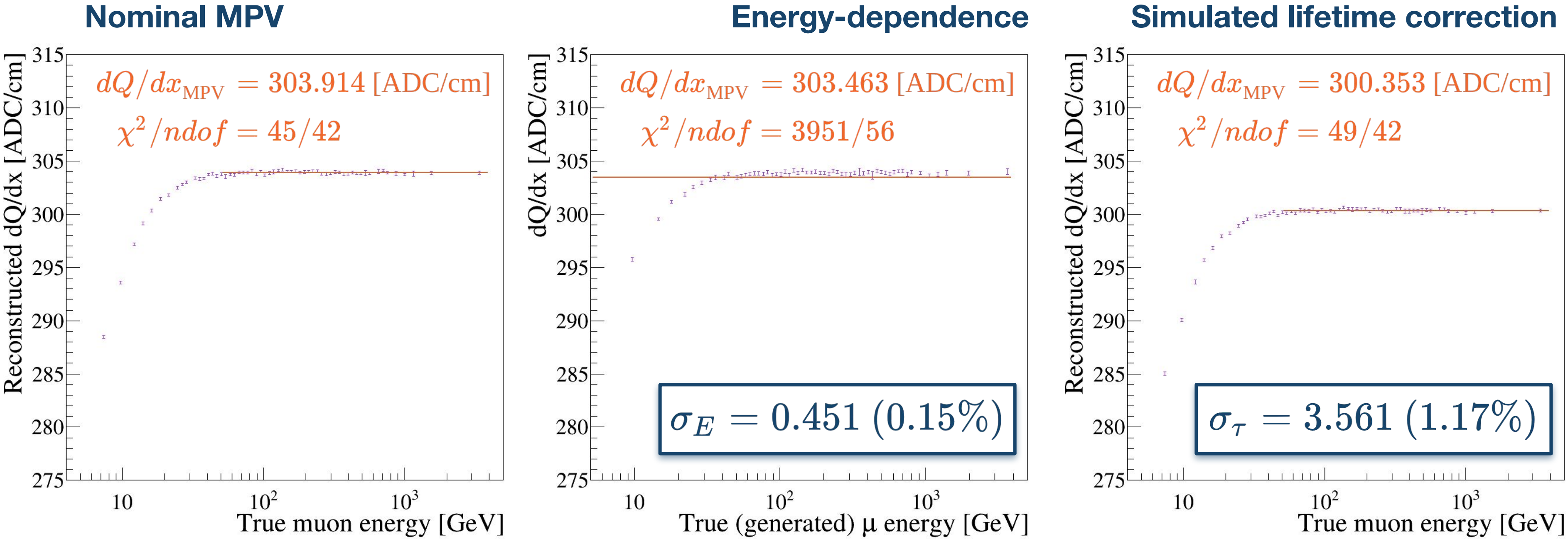
S = (6.16 ± 0.08) x10^{-3} [MeV/ADC] (stat+syst, 1.23%)

$dE/dx_{L\text{-}V}$ = 1.804 MeV/cm (μ: 292 GeV @ 5.3 mm thickness)



Systematic uncertainty contributions:
Energy-dependence of the charge depositions
Electron lifetime calculation

Systematics



$$\sigma_{E,\tau} = dQ/dx_{\mathrm{Nominal}} - dQ/dx_{E,\tau}$$

More details in at the [September CM]